Estimation of Sediment Properties Using Air Launched Sonobuoys

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LONG-TERM GOALS

The US Navy has been developing its Multi-Static Active Coherent (MAC) acoustic search system. MAC is an air launched acoustic search system that combines a newly developed coherent source sonobuoy with a field of receiver sonobuoys. With the introduction of the coherent source, operational search data collected during MAC exercises are well suited for post-processing to infer waveguide properties. The long term goal of this research is to investigate the feasibility of estimating sedient acoustic properties using data collected during such exercises.

OBJECTIVES

Modal dispersion data have been used in inversion schemes that estimate sediment properties in range-independent and range-dependent environments. The objective of this work is investigate and determine the source and receiver characteristics and other experimental parameters that are required to extract sediment properties with adequate resolution from mode dispersion data estimated from data collected during operational activities of the Navy.

APPROACH

In shallow water, wave guide acoustic propagation is best described in terms of the normal modes of propagation. Each of these modes travel along the waveguide at speeds which are dependent on the acoustic properties of the waveguide. The experimental set up to extract sediment acoustic properties consists of source that transmits broadband signals and several sonobuoy receiver systems. The acoustic field at a receiver placed at a distance from the source is then collected and processed to determine the group speeds of the modes at a set of discrete frequencies. This forms the data set used to obtain the acoustic properties of the waveguide. Typically one assumes that the water column properties are known by direct measurement and the only unknowns to be estimated are the acoustic characteristics of the bottom. The approach for estimating the sediment acoustic properties from dispersion relationship, i.e. the variation of the group speed of each mode as a function of frequency, has been detailed in [1, 2]. This procedure is a linearized solution which is based on perturbation theory. Consider a range-independent ocean model whose compressional wave speed and density are represented by $c_b(z)$ and $\rho_b(z)$, respectively. For this model $k_n(\omega)$ and $\phi_n(z,\omega)$ are the eigenvalue and mode function of the *n*th mode, respectively, that satisfy the depth-dependent Helmholtz equation and boundary conditions associated with the waveguide model. In these expressions *z* refers to the

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depth and ω the frequency of the acoustic source. Next, perturb the compressional wave speed by a small quantity $\Delta c(z)$. This will result in a change in the group speed of the propagating modes. The relationship between the group speeds of the nth mode due to a perturbation of the compressional wave speed is given by [1]

$$\frac{1}{\hat{v}_n(\omega)} - \frac{1}{v_n(\omega)} = \frac{\partial}{\partial\omega}\int_0^\infty \frac{-1}{k_n(\omega)} \frac{\omega^2 \Delta c(z)}{c_b^3(z)\rho_b(z)} \left|\phi_n(z,\omega)\right|^2 dz. \qquad (1)$$

In the above equation, v_n and $\hat{v}_n$ represent the group speeds of mode n for the unperturbed and the perturbed ocean models, respectively. By modeling the sediment as a discrete set of layers (1) can be re-written as a matrix equation of the form $\mathbf{Gm} = \mathbf{d}$ where **m** represents the corrections to the compressional wave speed values of the sediment layers, **d** the data which are the quantity on the left hand side of (1), and **G** are obtained by converting the integral in (1) to a sum. This matrix equation is ill posed and special care has to be taken to solve it. A means of regularization of the solution is required to obtain meaningful solutions to the matrix equation. Several approaches to regularization such as Tikhonov method [3] and its extension Qualitative Regularization [4] have been proposed. It has been shown in [2] that the formulation in (1) derived for range independent environment can be extended to range-dependent environment but it requires a multiplicity of source/receiver combinations to solve the problem. Other approaches to estimating the sediment acoustic properties using global optimization such as simulated annealing and genetic algorithm have also been implemented[5,6].

WORK COMPLETED

The issues posed by the use of this approach for estimating the sediment acoustic properties from a field of sonobuoys together with a compact source are:

- Method of generating a signal of sufficient bandwidth
- Estimating the group speed of modes using high resolution method
- Ability to estimate sediment properties when using data from high frequencies.
- Ability to extract range dependent sediment properties from a field of sonobuoys

A. Broad band signal generation

Broad band signals that have found wide acceptance are the LFM (Linear Frequency Modulated) signal in which the frequency is varied linearly either going up or down with the signal duration. Broadband signals are also created by pseudorandom sequences. The maximal length, binary, shift register sequences are pseudorandom sequences [7]. The shift register sequence generator consists of a shift register working in conjunction with appropriate logic, which feeds back a logical combination of two or more of its stages to its input. The output of the sequence generator and the contents of its stages at any sample time is a function of the stages fed back at the preceding sample time. If there are n stages in the shift register, the maximal length sequence is a unique sequence of ones and zeros of length $N=2^n-1$ before repeating itself. For creating a broad band signal the zeros in the sequence is changed to -1, i.e. we now have a sequence of 1 and -1 and then the 1 are replaced by a chip and the -1 are replaced by phase shifted version of the chip.

B. Simulation of data

Let us consider an ocean model where the water column is 70 m in depth and the sediment consists of three layer. The thicknesses of the three layers are 8 m, 16 m and 8 m respectively. This is terminated by a half space of constant compressional wave speed and density. The sound speed in the water column is 1480 m/s, the compressional wave speed in the three layers are 1569 m/s,1705 m/s, and 1527 m/s respectively. The densities in all the layers are 1.6 gm/cc. The compressional wave speed in the terminating half space is 1850 m/s and density 1.6 gm/cc. Attenuation in the sediment layers and in the half space have been neglected.

The data were simulated using this ocean model. A broad band signal was created using pseudorandom maximum length sequence of length 511.The sequence of 1 and -1 is used to modulate a carrier signal with a frequency of 500 Hz and each digit in the sequence is chip of length one cycle at 500 Hz. The sampling frequency was 2500 Hz. A time domain acoustic signal at the receiver can be modeled by Fourier synthesis of the frequency domain solution to the acoustic wave equation $p(r,z,\omega)$.

$$p(r,z;t) = \int_{-\infty}^{\infty} S(\omega) p(r,z;\omega) \exp(i\omega t) d\omega, \qquad (2)$$

where $S(\omega)$ is the spectrum of the transmitted signal and $p(r,z;\omega)$ is the frequency domain solution at range r and depth z. To compute the time domain solution above requires that $p(r,z;\omega)$ be calculated at a number of discrete frequencies, which span the frequency band of the source spectrum. The ocean environment was the input to the normal mode code KRAKEN [8] for computing the frequency domain solution with the range to the receiver, depths of the source and receiver set as required.

C. Estimation of group speed of modes

The group speeds as a function of mode number and frequency can be obtained from a knowledge of the mode eigenvalues and mode functions [9]. This assumes that the environment is fully known. In a field experiment designed to estimate the mode dispersion, a broadband signal is broadcast by a source placed in the shallow water waveguide and the signal at a receiver placed at a distance from the source is collected and processed. The group speed as a function of frequency and mode is obtained by performing short time Fourier transform (STFT) of the received signal. The squared modulus of the STFT is called the spectrogram. Such a transform provides the time for the modes to travel from source to receiver from which the mode group speeds are obtained. If the distance between the source and receiver is large, the modes are fully resolved and it is not problematic to estimate the mode dispersion curves from the spectrogram. When the range to receiver is short, the modes are not well resolved and a high resolution method must be used to resolve the modes. The high resolution method proposed in [10, 11] involves applying warping operator to the received signal.

In Figure 1, two of the five steps of the warping procedure are shown. The top left panel in the figure is the impulse response obtained from the received signal. The top right panel shows the signal to which the warping operator has been applied. The bottom left panel shows the spectrogram of the received signal. While the lower order modes are easily distinguished, the higher order modes are not well resolved. The bottom right panel the shows time-frequency representation of the warped signal. The modes appear as pure tones and are well resolved. The modes can be filtered by simply masking modes those that are not of interest. The filtered modes are then processed to estimate the mode dispersion data for the filtered mode. This procedure provides robust estimates of the mode dispersion at frequencies above the Airy phase. The ability of inverse procedure to estimate the sediment properties in deeper layers depends on the mode function having sufficient magnitude at these depths.

This requires inclusion of modes below the Airy phase frequencies. Some improvement in this regard is obtained by using STFT modified to take into consideration the dispersive nature of the medium [12]. Another scheme for extracting the full dispersion data has been proposed [13] and this is being investigated.

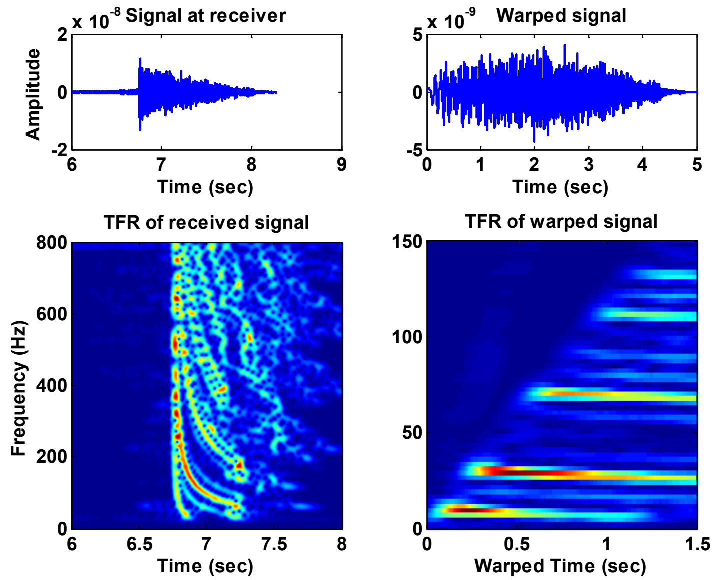

Fig. 1 The top left panel is the impulse response of the channel to the transmitted signal. The topright panel shows the time warped signal.The bottom left panel is the spectrogram of the impulse response. The bottom right panel is the short time Fourier transform (STFT) of the warped signal.

RESULTS

The main objective of this work is to investigate the feasibility of extracting sediment properties from data aquired by a distributed network of sonobuoys. The source that is likely to be deployed is a compact coherent source. While the details such as the bandwidth of such source is not known, the tests for geoacoustic inversion was done assuming that the source will have a bandwidth of about 200 Hz.The inversions were carried out with mode dispersion data in the frequency intervals 50 Hz – 150 Hz, 100 Hz – 300 Hz and 300 Hz – 500 Hz.

A. Inversion based on perturbation theory.

The inversion for the sediment compressional wave speed profiles were perfored using six different sets of data. These are (a) noise free data in the frequency inertvals 50 Hz – 150 Hz, 100 Hz – 300 Hz, and 300 Hz – 500 Hz, (b) data with noise in the frequency inerval 100 Hz – 300 Hz, and (c) data from short range (5 km range) in the frequency inervals 50 Hz -150 Hz and 100 Hz – 300 Hz.

The unknowns to be estimated are the compressional wave speed values in the three layers. All the other parameters were assumed known. The data used in the inversion are shown in Fig 2. The results of inversion are shown in Fig 3. The plots 3(a), 3(b), and 3(c) in the figure are the inversion results in which data were obtained from noise free signal at the receivers. It is seen that the inverse resulted in estimating the compressionalwave speed in the three layers without any significant error when data from frequency intervals 50 Hz -150 Hz and 100 Hz – 300 Hz were used. However, when data from 300 Hz -500 Hz were used the inversion could not estimate the compressional wave speed in the third

layer. In this case the magnitude of the mode function at depths corresponding to the deeper layers is near zero and hence the inversion procedure was not able to estimate the layer speed in the third sediment layer.

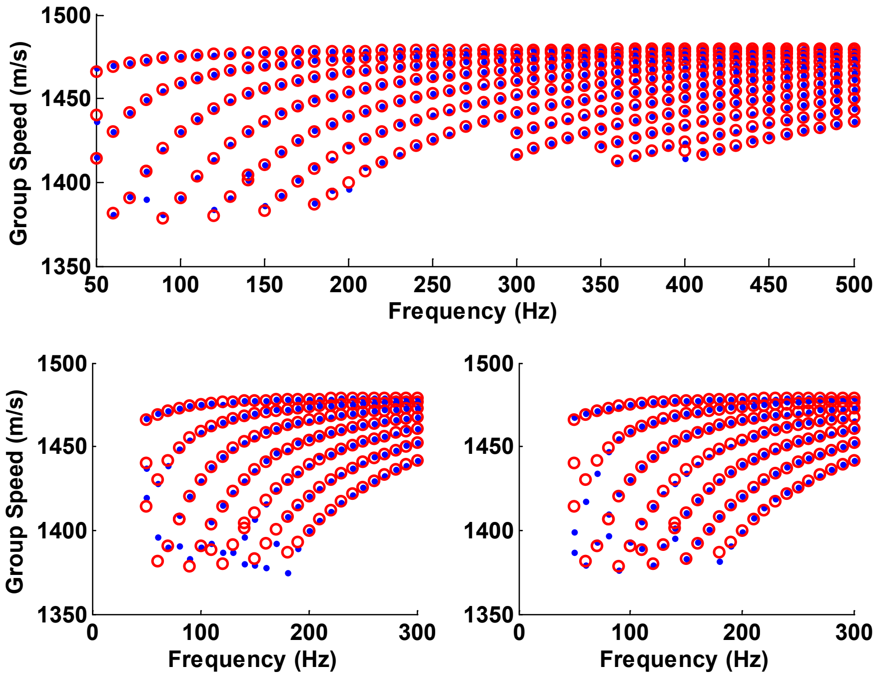

Fig. 2. The top panel shows the estimates of group speed of modes 1 to 12 for frequencies from 50 Hz to 500 Hz. The blue dots are the values obtained by analysis of the noise free received signal using the warping method and the red circle denotes the values obtained from theory. The bottom left panel shows the data for modes 1 to 7 for frequencies from 50 Hz to 300 Hz in the case where noise has been added to the data. The bottom right panel shows the data when a range to receiver is short (5 km).

We now examine the effect of noise in the data. Gaussian random noise with SNR of 5dB was added to the noise free signal at the receiver. The group velocities estimated from the noisy signal are compared with the true group speed in the bottom left panel of Fig 2. It is seen that there are a number of data points where the estimate of group speeds from the noisy signal are in error. In order to perform the inversion with this data, these data points were assumed to have larger variance in their values and this was incorporated in the inversion scheme. The result of the inversion using the noisy data is shown in Fig 3(d). It is seen that noise in the data results in large error in the estimation of the layer speeds. The data for the analysis discussed so far had been obtained with the source to receiver range set at 10 km or more. Since in field experiment such a large aperture may not be possible, data was simulated with the source to receiver range set at 5 km. The group speed estimated from the simulated data with range set at 5 km and the true speeds are shown in the bottom right panel of Fig 2. The results of inversion using this data are shown in Fig 3(e) and 3(f). In this case the inversions in the frequency interval 100 Hz – 300 Hz shows larger errors in the group speed of the layers as compared to 3(b) which is the case for larger range.

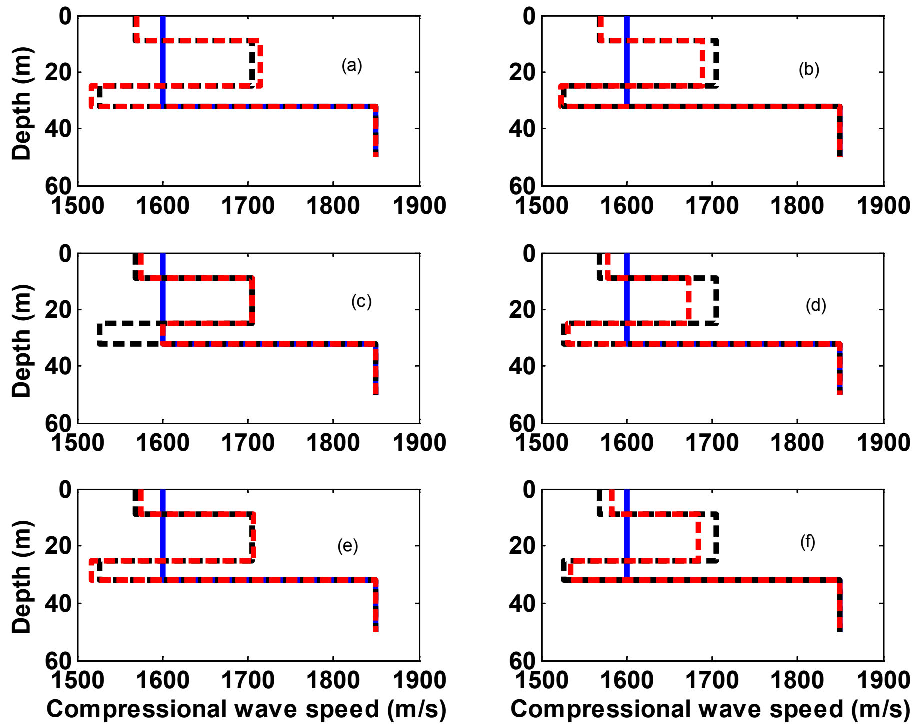

Fig. 3. The figure shows the staring model (blue firm line), the true bottom model (black dashed line), and the inversion result (red dashed line). The figures (a), (b) and (c) use data estimated from the time frequency analysis of the noise free signal acquired at the receiver for frequencies 50 Hz - 150 Hz, 100 Hz – 300 Hz, and 300 Hz -500 Hz respectively. The figure (d) has the result for data from noisy signal for frequencies 100 Hz – 300 Hz. The figures (e) and (f) uses data from signal acquired at a range of 5 km for frequencies 50 Hz – 150Hz and 100 Hz – 300 Hz respectively.

B. Inversion based on global optimiation.

Inversion can also be treated as a parameter estimation problem where the attempt is to find the bottom model that predicts the measured quantity with minimum error. Specifically let $\boldsymbol{d_k}$ be a vector containing the data, i.e. a vector of the group speed for a set of frequencies in the case of the kth mode as determined from field measurements. For a given bottom model $\boldsymbol{m}$ which contains the parameters to be estimated, the calculated group speed of mode k is $\widehat{\boldsymbol{d}}_{\boldsymbol{k}}(\boldsymbol{m})$. The vector $\boldsymbol{m}$ contains the sediment properties that are to be estimated. The estimation problem then reduces to the determination of the parameters of $\boldsymbol{m}$ that minimizes $\sum_1^K \left|\boldsymbol{d_k} - \widehat{\boldsymbol{d}}_{\boldsymbol{k}}(\boldsymbol{m})\right|^2$. The most commonly used global optimization methods that have been used to solve problems of this kind are (a) Simulated annealing and (b) Genetic algorithm and their variants.

We use the Genetic algorithm to estimate the compressional wave speed in the sediment layers and in the half space. More detailed explanation of the procedure used in the execution of Genetic Algorithm can be found in [14]. The search bounds and the estimates of the parameter values are in Table 1. These values were obtained using the simulated data without and with noise in the frequency interval 50 Hz to 150 Hz.

Table 1: The results of inversion using genetic algorithm				
Type of data	**Parameter**	**Parameter Value (m/s)**	**Search bound (m/s)**	**Inversion result**
50 Hz – 150 Hz (No noise)	Layer 1	1569.0	1500 - 1800	1575.0
	Layer 2	1705.0	1500 - 1800	1714.0
	Layer 3	1527.0	1500 - 1800	1521.0
	Half space	1850.0	1800 - 2000	1852.5
50 Hz -150 Hz (Noise added)	Layer 1	1569.0	1500 - 1800	1584.0
	Layer 2	1705.0	1500 - 1800	1710.0
	Layer 3	1527.0	1500 - 1800	1523.0
	Half space	1850.0	1800- 2000	1918.0

CURRENT WORK

One of the drawbacks of the warping method for extraction of the mode dispersion data is its inability to determine the mode dispersion at frequencies below that of the Airy phase for that mode. A scheme has been proposed [13] that will enable extraction of the complete mode dispersion data. The scheme uses a tiling in the time-frequency plane which accounts for dispersion. The change in the tiling requires a knowledge of the group velocity dispersion. Investigations on the applicability of this scheme by the use of approximate values of the group velocity disperson is under investigation. Further another approach suggested in [15] is also being persued. A comprehensive investigation is also needed to study the impact of imperfect knowledge of the water column properties, bathymetry between source and receiver and other environmental parameters on inversion for sediment properties. estimation.

IMPACT/APPLICATIONS

The data collected during this experiment will enable validation of the proposed method for estimating range-dependent sediment compressional wave speed from modal dispersion data. Using a distributed set of receivers and a broadband source it will be possible to estimate the compressional wave speed profiles over a wide area. This will therefore be a useful tool for estimating the sediment acoustic properties from data collected during routine naval operations.

RELATED PROJECTS

The estimation of sediment properties in a shallow water environment is an active area of research. The new procedures that are likely to come out of this work will therefore be of great benefit.

REFERENCES

1. S. D. Rajan, J. F. Lynch, and G. V. Frisk, "Perturbative inversion methods for obtaining bottom geoacoustic parameters in shallow water," Journal of the Acoustical Society of America, 82(3), 998-1017, 1987.

2. S. D. Rajan and K.M. Becker, "Inversions for range-dependent sediment compressional wave speed profiles from mode dispersion data," IEEE Journal of Oceanic Engineering, 35(1), 43-58, 2010.

3. Inverse Problem Theory and Methods of Parameter Estimation, A. Tarantola, SIAM, Philadelphia, 2005.

4. L. Simcik and P. Lin, "Qualitative regularization: Resolving non-smooth solutions." Tech Report CSE 94-12, University of California, Department of Mathematics.

5. P. Gerstoft, "Inversion of seismoacoustic data using genetic algorithms and posterior probability distributions," Journal of the Acoustical Society of America, 95,770-782, 1994.

6. C. E. Lindsay and N. R. Chapman, "Matched field inversion for geoacoustic model parameters using adaptive simulated annealing," IEEE, Journal of Oceanic Engineering, 18,224-231, 1993.

7. Spread spectrum systems with commercial applications, R. C. Dixon, John Wiley & Sons, 1994.

8. M. Porter, The Kraken Normal Mode Program, Saclant Under Sea Research Center, La Spezia, Italy, Tech Report SM245, 1991.

9. D. M. F. Chapman and D. D. Ellis, "The group velocity of normal modes," Journal of the Acoustical Society of America, 74, 973-979, 1983.

10. J. Bonne, B. Nicolas, J. Mars and S. C.Walker, "Estimation of modal group velocities with a single receiver for geoacoutic inversion in shallow water," Journal of the Acoustical Society of America, 128, 719-727, 2010.

11. J. Bonnel, S. E. Dosso and N. R. Chapman, "Bayesian geoacoustic inversion of a single hydrophone light bulb data using warping dispersion analysis," Journal of the Acoustical Society of America, 134,120-130, 2013.

12. J. C. Hong, K.H. Sung and Y. Y.Kim, "Dispersion based short time Fourier transform applied to dispersive wave analysis," Journal of the Acoustical Society of America,117, 2949 – 2960, 2005.

13. L. De Marche, A. Marani, S. Caporole and N.Speciale, "Ultrasonic guided waves characterization with warped frequency transform," IEEE Transactions on UFFC, 56, 2232-2240, 2009.

14. Global Optimization methods in geophysical inversion, Sen and P. L. Stoffa, Elsevier, 1995.

15. J. Bonnel, B. Nicolas, J. Mars and D. Fattaciolli, "Frequency warping for waveguide characterization in a single hydrophone," MTS/IEEE, Oceans 2009.